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Improvement of the Dynamic Characteristics of Au-free AlGaN/GaN Schottky Diodes on 200 mm Si Wafers by Surface Treatments

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***Abstract*— In this work we show the impact of surface cleaning on the dynamic characteristics of Au-free AlGaN/GaN Gated Edge Termination Schottky Barrier Diodes (GET-SBDs). It is demonstrated that the current dispersion (measured in pulsed regime) can be reduced by introducing a N_2 plasma cleaning step in the anode metal deposition chamber. Moreover, diodes treated with N_2 plasma show lower current drop after reverse voltage stress (with a relative forward voltage increase of 2% after stress) than diodes without clean or with Atomic Layer Etching (ALE) clean (20% and 37% relative forward voltage increase, respectively).**

I. INTRODUCTION

AlGaN/GaN Schottky Barrier Diodes (SBDs) are being explored due to their high current and high voltage capabilities, combined with high switching speed [1-5]. To this purpose, controlling the Schottky contact by appropriate surface treatments is fundamental for achieving good dynamic characteristics. We have reported on Au-free, high performance AlGaN/GaN Schottky Barrier Diodes (SBDs) with Gated Edge Termination (GET-SBDs) on 200 mm Si substrate [1,2]. In our previous work and in most papers on AlGaN/GaN SBDs [3-5], the DC characteristics of the diode are discussed. In this work a study on the diode dynamic behavior is performed. We demonstrate that surface cleaning prior to anode metal deposition is a crucial factor in improving the diode performance. Literature reports on nitrogen plasma-based treatments, applied to the AlGaN surface of AlGaN/GaN High Electron Mobility Transistors (HEMTs), to reduce the current dispersion [6,7]. It is also reported that, in case of N_2 plasma with low power, the active N_2 radicals in the plasma can help recovering the (Al)GaN surface stoichiometry by reacting with impurities present at the surface [8]. In this work a N_2 plasma treatment is applied to AlGaN/GaN GET-SBDs, *in-situ* on the III/nitride surface prior to the Schottky metal deposition, in order to improve the Schottky contact and reduce current dispersion phenomena. As an alternative for removing the surface impurities, Atomic Layer Etching (ALE) is also explored. N_2 plasma cleaning results to be more effective than ALE in improving the dynamic characteristics (pulsed I-V and reverse stress) of AlGaN/GaN GET-SBDs.

II. DEVICE FABRICATION

Fig. 1 shows a scheme of the diode, fabricated on top of a 200 mm Si wafer. The Si_3N_4 edge termination is indicated in the figure: this dielectric layer at the anode corners acts as a shielding element which redistributes the electric field, reducing the reverse leakage current [1,2]. In forward conduction mode, high current can flow through the Schottky contact in the center of the anode region. Fig. 2 shows the anode processing. On top of 200 mm <111> Si wafers, the following epitaxial layers were grown by Metal Organic Chemical Vapor Deposition (MOCVD): 200 nm AlN nucleation layer (on top of the Si substrate), followed by a 2600 nm-thick AlGaN-based buffer, 150 nm-thick GaN channel and 10 nm-thick $Al_{25}Ga_{75}N$ barrier. The epitaxial stack was passivated with a 140 nm-thick Si_3N_4, grown by Rapid Thermal Chemical Vapor Deposition (RTCVD). Then, the GET anode was fabricated. After opening the anode region in the Si_3N_4 surface passivation, a 15 nm-thick RTCVD Si_3N_4 was deposited at 650ºC and annealed at 700ºC (Fig. 2(a)).

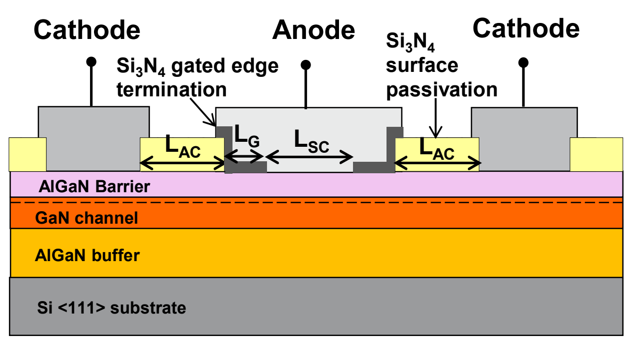

Figure 1. Schematic representation of the GET-SBD.

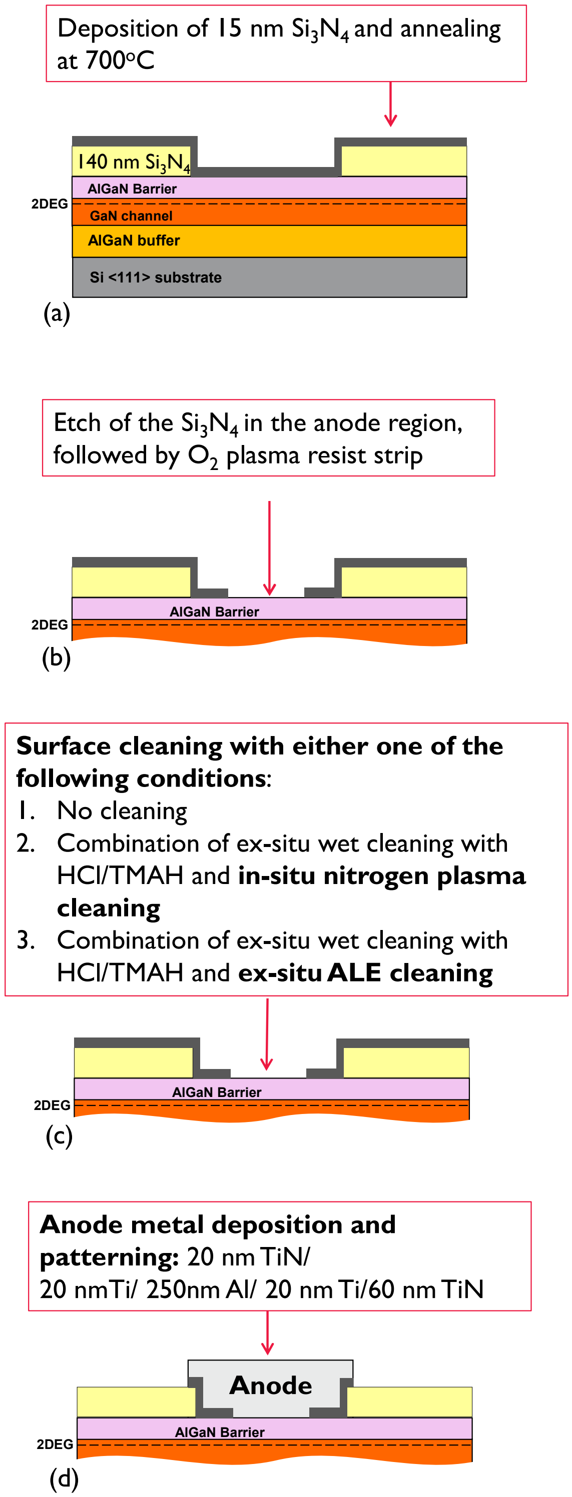

Figure 2. Anode process flow, highlighting the cleaning step.

The Si_3N_4 edge termination was etched open by SF_6 dry etching to define the Schottky contact (Fig. 2(b)). Then, three types of cleaning were tested (Fig 2(c)):

1. No cleaning, as a reference.
2. Wet cleaning with HCl (10 min, 18 wt%) and TMAH (10 min, 65°C), followed by *in-situ* N_2-based plasma cleaning inside the anode metal sputtering tool (i.e. without air break before the metal deposition). The N_2 plasma conditions were 100W RF power, 50W bias power and 36 sccm N_2 flow.
3. One cycle ALE cleaning, followed by wet cleaning with HCl (10 min, 18 wt%) and TMAH (10 min, 65°C). ALE cleaning is a sequence of plasma oxidation steps of the AlGaN, followed by removal of the oxidized layer in BCl_3: in this case, 1 cycle (i.e. 1 oxidation and 1 removal step) was applied.

The anode metal, subsequently deposited and patterned, consists of a 20 nm TiN / 20 nm Ti / 250nm Al / 20 nm Ti / 60 nm TiN Au-free stack, as illustrated in Fig 2(d).

The processing continued with the Au-free cathodes (a Ti/Al/Ti/TiN-based stack, annealed at 550 ºC) and Au-free backend [1].

III. Device Characterization

DC characterization was performed on GET-SBDs with anode finger width of 100 µm, anode-cathode distance L_{AC}= 10 µm, length of the edge termination L_G= 1.5 µm and Schottky contact dimension L_{SC}= 6 µm (see Fig.1). Fig. 3 shows typical DC characteristics, measured by an Agilent 4156C parameter analyzer, of GET-SBDs without clean, with N_2-based plasma clean and with ALE clean.

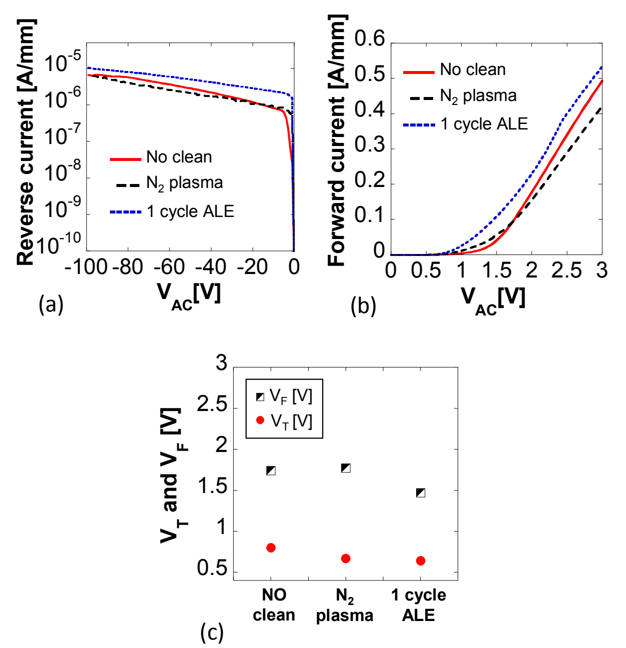

Figure 3. DC reverse (a) and forward (b) curves. Turn-on voltage V_T and on-state voltage V_F for the three cleaning conditions (c).

Fig. 3 (a) and (b) illustrate the DC reverse and forward current, as a function of the anode-cathode voltage V_{AC}, of GET-SBDs without clean (red solid curves), with N_2 plasma clean (black dashed curves) and with ALE clean (blue dotted curves). The turn-on voltage V_T (i.e. V_{AC} extracted at a forward current level of 1 mA/mm) and on-state voltage V_F (i.e. V_{AC} at 100 mA/mm) for the 3 different process conditions are shown in Fig. 3 (c). Although the ALE clean shows lower on-state DC voltage, this treatment is not effective in reducing the current collapse, as shown in Fig. 4.

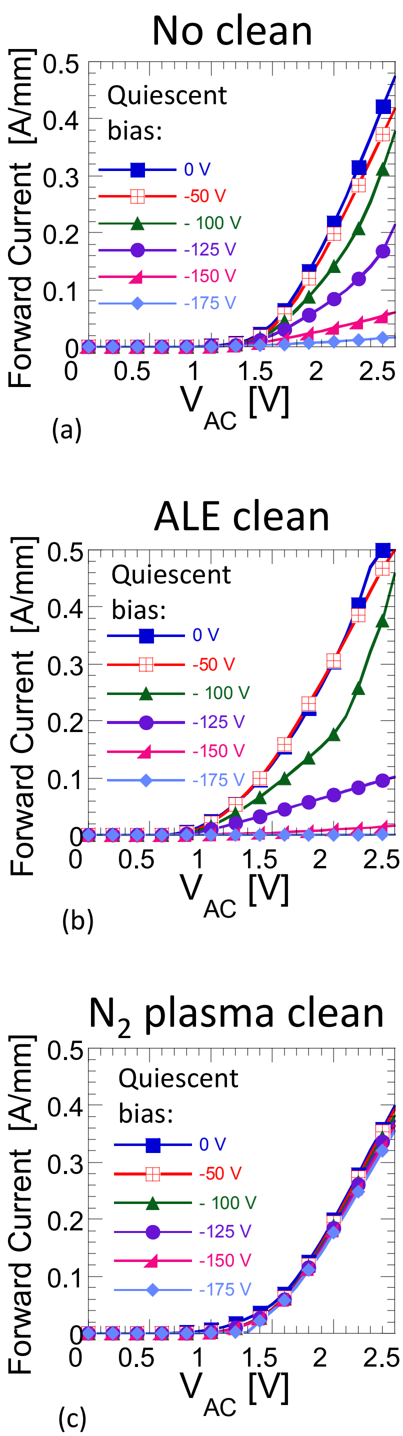

Figure 4. Pulsed IV curves (for the different quiescent bias values) of GET-SBDs without clean (a), with ALE clean (b) and with N_2 plasma clean (c). The anode finger width of the diodes is 100 μm.

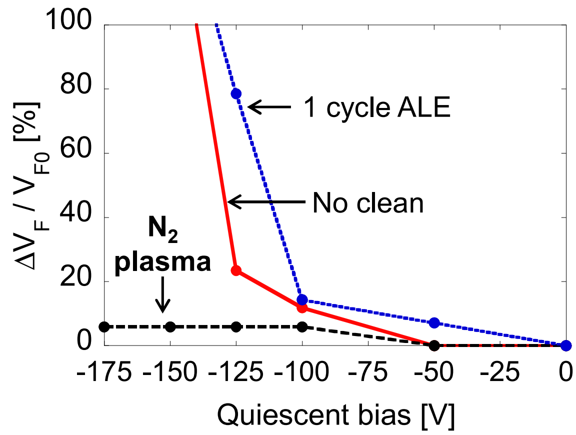

Figure 5. Relative on-state voltage increase for the three cleaning conditions: No clean (red, solid curve), ALE treatment (blue, dotted curves) and N_2 plasma (black, dashed curves).

Dispersion characterization was performed by means of an Agilent B1505A parameter analyzer on GET-SBDs. The devices have anode finger width of 100 μm, L_{AC}= 5 μm, L_G= 1.5 μm and L_{SC}= 6 μm. The anode-to-cathode voltage V_{AC} was pulsed from forward operation to a reverse quiescent bias, which ranges from 0 to -175V (pulse timing: 10 ms in reverse quiescent bias and 2 ms in forward). The current collapse of the output characteristics was assessed. Fig. 4 shows the pulsed IV curves for the three different cleaning conditions. While strong current collapse is observed in the case of anode processing without cleaning (Fig. 4 (a)) or ALE treatment (Fig. 4 (b)), limited collapse occurs when in-situ N_2 plasma cleaning is applied (Fig. 4 (c)). The relative on-state voltage increase $\Delta V_F/V_{F0}$ was extracted as a function of the reverse quiescent bias (Fig. 5). V_{F0} is the on-state voltage at 0 V quiescent bias and ΔV_F is the difference between V_F at a given quiescent bias and V_{F0}. The results are plotted in Fig. 6 and show a relative increase of more than 100% at -150V, in case of diode without clean or with ALE. Instead, when the surface is treated with N_2 plasma, the relative increase is about 6% at -175 V.

Reverse stress tests were performed on GET-SBDs with anode finger width of 1 mm, L_{AC}= 5 μm, L_G= 1.5 μm and L_{SC}= 6 μm. The diodes were first measured in DC with V_{AC} ranging from 0 to 3V. Then, a reverse bias V_{AC}= -150V was applied for 1 min. After that, the forward characteristic was measured again.

Fig. 6 shows the forward IV characteristics, for the three surface treatments, on a fresh device (black, solid curves) and after 1 min reverse stress (red, dashed curves). The on-state voltage increase ΔV_F is indicated in each graph. The diode without clean and the one with ALE clean show a relative forward voltage increase (i.e. ΔV_F normalized to the V_F value before stress) of 20% and 37%, respectively (Fig. 6 (a) and (b)). Instead, when the diode is treated with N_2 plasma (Fig. 6 (c)) the increase is only 2%.

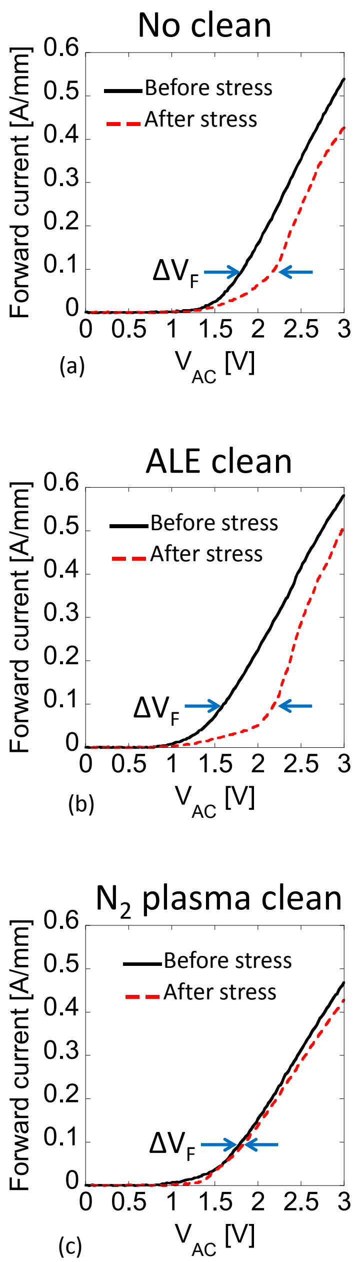

Figure 6. DC characteristics, before and after reverse stress, of GET-SBDs without clean (a), with ALE clean (b) and with N_2 plasma clean (c). Black, solid curves indicate a fresh device, while red dashed curves show devices measured after 1 min reverse stress

IV. Conclusions

The impact of different anode surface cleaning techniques on Au-free AlGaN/GaN GET-SBDs was assessed. The introduction of an *in-situ* N_2 plasma treatment at low power prior to the anode metal deposition resulted into reduced current collapse in pulsed mode (relative on-state voltage increase of 6% at -175V), as compared with 1 cycle of ALE or a reference sample without clean. Moreover, diodes treated with N_2 plasma show higher robustness to reverse stress.

Acknowledgment

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